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(54) Title: FAST TORQUE RESPONSE FOR BOOSTED ENGINES

FIG. 3

(57) Abstract: Engine controllers and control schemes are provided for managing engine state transitions requiring increased compressor pressure ratios in turbocharged engines operating in a cylinder output level modulation mode (e.g., skip fire, multi-level skip fire, or firing level modulation modes). In some circumstances, turbo lag can be mitigated by initially transitioning the engine to an intermediate effective firing density that is higher than both the initial and target effective firing density to increase the flow of gases through the engine and the turbocharger while maintaining a compressor ratio the same as or close to the initial compressor pressure ratio. After reaching a point where the desired torque is actually generated at the intermediate effective firing density, the operational effective firing density is gradually reduced to the target effective firing density while increasing the operational compressor pressure ratio to the target compressor ratio.

FAST TORQUE RESPONSE FOR BOOSTED ENGINES

CROSS-REFERENCE TO RELATED APPLICATION

[0001]   This application claims the benefit of U.S. Patent Application No. 17/080,082, filed October 26, 2020, which is incorporated herein by reference for all purposes.

BACKGROUND

[0002]   The present application relates to the use of cylinder output level modulation (e.g. skip fire and/or Hi/Lo fire) in turbocharged engines to help improve torque response in a fuel efficient manner.

[0003]   Most vehicles in operation today (and many other devices) are powered by internal combustion (IC) engines. Internal combustion engines typically have a plurality of cylinders or other working chambers where combustion occurs. Under normal driving conditions, the torque generated by an internal combustion engine needs to vary over a wide range in order to meet the operational demands of the driver.

[0004]   The fuel efficiency of many types of internal combustion engines can be improved by varying the displacement of the engine. This allows for the full torque to be available when required, yet can significantly reduce pumping losses and improve thermodynamic efficiency through the use of a smaller displacement when full torque is not required. The most common method of varying the displacement of an engine involves deactivating a group of cylinders substantially simultaneously. In this approach, no fuel is delivered to the deactivated cylinders and their associated intake and exhaust valves are kept closed as long as the cylinders remain deactivated.

[0005]   Another engine control approach that varies the effective displacement of an engine is referred to as "skip fire" engine control. In general, skip fire engine control contemplates selectively skipping the firing of certain cylinders during selected firing opportunities. Skip fire engine operation is distinguished from conventional variable displacement engine control in which a designated set of cylinders are deactivated substantially simultaneously and remain deactivated as long as the engine remains in the same variable displacement mode. Thus, the sequence of specific cylinders firings will always be exactly the same for each engine cycle during operation in a variable displacement mode (so long as the engine remains in the same displacement mode), whereas that is often not the case during skip fire operation.

[0006]   Boosted engines (e.g., engines having turbochargers or superchargers) have unique requirements and challenges. The present application describes engine control features and

enhancements that can improve the performance of boosted engines in a variety of applications using skip fire or other cylinder output level modulation techniques.
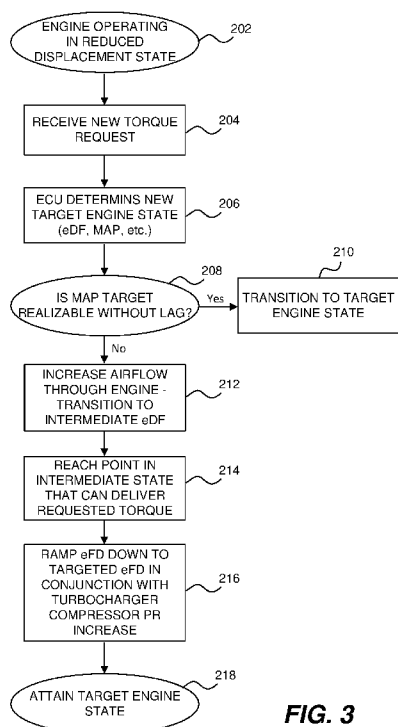
SUMMARY

[0007]   Engine controllers and control schemes are provided for managing engine state transitions requiring increased compressor pressure ratios in turbocharged engines operating in a cylinder output level modulation mode (e.g., skip fire, multi-level skip fire, or firing level modulation modes). In some circumstances, turbo lag can be mitigated by initially transitioning the engine to an intermediate effective firing density that is higher than both the initial and target effective firing density to increase the flow of gases through the engine and the turbocharger while maintaining a compressor ratio the same as or close to the initial compressor pressure ratio. After reaching a point where the desired torque is actually generated at the intermediate effective firing density, the operational effective firing density is gradually reduced to the target effective firing density while increasing the operational compressor pressure ratio to the target compressor ratio.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008]   The invention and the advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawings in which:

[0009]   FIG. 1 is a representative radial compressor efficiency map for a production turbocharger.

[0010]   FIGS. 2A-2E are a series of graphs diagrammatically illustrating a control scheme for controlling transient response to certain engine or cylinder torque increase requests in a turbocharged engine.

[0011]   FIG. 3 is a flow chart illustrating a method of controlling transient response to certain engine or cylinder torque increase requests in a turbocharged engine.

[0012]   In the drawings, like reference numerals are sometimes used to designate like structural elements. It should also be appreciated that the depictions in the figures are diagrammatic and not to scale.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0013]   In general, skip fire engine operation facilitates finer control of the effective engine displacement than is possible using a conventional variable displacement approach. For example, firing every third cylinder in a 4 cylinder engine would provide an effective displacement of $1/3^{rd}$ of the full engine displacement, which is a fractional displacement that is not obtainable by simply deactivating a set of cylinders. Conceptually, virtually any effective

displacement can be obtained using skip fire control, although in practice most implementations restrict operation to a set of available firing fractions, sequences or patterns. When discussing skip fire engine operation, reference is often made to the firing fraction (FF) which is the fraction or percentage of cylinder working cycles that are actually fueled and fired (e.g., 1/3, 2/5, ¾, etc.).

[0014]   The Applicant has developed a technology referred to as dynamic skip fire (DSF) in which firing decisions are made on a cylinder firing opportunity by cylinder firing opportunity basis. In many applications, a single firing decision is made at a time, whereas in others, firing decisions for small sets of cylinders may be made at the same time (e.g., a engine cycle by engine cycle basis). Various aspects of dynamic skip fire are described in a number of patents including U.S. Patent Nos. 7,954,474, 7,886,715, 7,849,835, 7,577,511, 8,099,224, 8,131,445, 8,131,447, 8,616,181, 8,701,628, 9,086,020, 9,328,672, 9,387,849, 9,399,964, 9,512,794, 9,745,905, and others, each of which is incorporated herein by reference. Cylinders are typically deactivated during skipped working cycles so that air is not pumped through cylinders during the skipped cycles and there are a variety of different valve actuation management schemes that may be used to accomplish such deactivation.

[0015]   The individual cylinder control concepts used in dynamic skip fire can also be applied to multi-charge level engine operation in which all cylinders are fired, but individual working cycles are purposely operated at different cylinder output levels. In two-step multi-charge level engine operation, cylinder working cycles can be selectively fired at either a "high" output level, or a "low" output level which generates less torque than a "high" firing. When discussing two-step multi-charge level engine operation, reference is often made to the high fire fraction (HF) which refers to the fraction or percentage of the fired working cycles that are fired at the high output level.

[0016]   Skip fire and multi-charge level engine operation can be combined in multi-level skip fire engine operation to deliver additive and synergistic fuel consumption improvements. In general, multi-level skip fire contemplates that individual working cycles of an engine may be selectively fired or skipped during individual cylinder working cycles and that fired working cycles may be purposely operated at different cylinder outputs levels in an interspersed manner. In two-step multi-charge level engines, a two-step intake valve lift system is used. In multi-level skip fire operation, the valve control system further has the ability to deactivate a cylinder by deactivating the intake valve(s) during selected cylinder working cycles.

[0017] Skip fire, multi-level skip fire, and multi-charge level engine operation may collectively be considered different types of cylinder output level modulation engine operation in which the output of each working cycle (e.g., skip/fire, high/low, skip/high/low, etc.) is varied during operation of the engine. Sometimes the firing decisions are made dynamically on an individual cylinder working cycle by working cycle (firing opportunity by firing opportunity) basis or in small sets such as on an engine cycle by engine cycle basis. The Applicant has described multi-charge level and multi-level skip fire engine operation in a number of patents and patent applications including U.S. Patent Nos. 9,399,964, 9,476,373, U.S. Patent Application No. 63/043,253, and others, each of which is incorporated herein by reference.

[0018] Two-step mDSF combines two-step multi-charge level and DSF. In mDSF, both the firing fraction and the high fire fraction are relevant. When the use of multiple non-zero firing levels is contemplated (e.g., during multi-level skip fire or multi-charge level operation of an engine), it is often helpful to consider an effective firing density (eFD) which correlates to the percentage or fraction of the cylinders that would be fired at a high or reference output. For example, if half of the cylinders are fired at a cylinder output level of 70% of a full firing output and the other half are fired at the full firing output level, then the effective firing density would be 85%. This corresponds to a Firing Fraction of 1.0 and a High fire fraction of 0.5. If the "Low" cylinder output were reduced to 60% of a full firing, then the effective firing density would be reduced to 80% in this example.

[0019] Downsized, boosted engines are currently a popular powertrain choice for passenger vehicles. Technologies such as multi-charge level and Skip Fire engine operation improve fuel consumption in part by operating at higher manifold pressures (MAP), which reduces pumping losses. For maximum benefit in boosted engines, both preferably operate in boost to some extent. A challenge that occurs in both technologies is that airflow will generally be lower at a given intake manifold pressure (MAP) or compressor pressure ratio (PR). Multi-level skip fire will tend to further increase the MAP and boost demand.

[0020] Fig. 1 shows a representative radial compressor efficiency map from a production turbocharger. As can be seen in the graph, higher compressor pressure ratios generally require higher mass flow rates of exhaust gases through the engine. In general, higher pressure ratio (PR) vs mass flow requirement means traversing the compressor map more vertically, which has the effect of reducing compressor efficiency and requiring higher compressor speeds. During an increasing torque and MAP transient event, these two requirements result in increased turbocharger lag and an associated torque delay (sometimes referred to as torque sag) because of

the feedback loop between the turbine, compressor and engine. This applies to an increasing engine torque event, such as an accelerator tip-in, or an increasing cylinder torque event, such as transitioning to a lower firing fraction. The compressor would also generally operate closer to the surge line (top boundary of compressor map) in such circumstances.

[0021]   In an mDSF engine, it is possible to leverage dynamic charge management (Hi/Lo Fire or HF) and dynamic skip fire to improve the initial torque response while simultaneously reducing the turbo lag to reach the boosted fuel-optimal steady-state point in a timely manner. Conceptually, the goal is to temporarily increase the flow rate of air/gases through the engine at a lower compressor PR and MAP and thereby deliver more energy into the turbocharger turbine while extracting less power from the compressor. This allows the turbine to spin up more quickly and can be achieved through a combination of increasing one or more of the firing fraction (FF), the high fire fraction (HF) and/or the intake/exhaust cam phasing. Once the turbine speed has been increased sufficiently, the compressor pressure ratio may be increased more aggressively. The strategy can be implemented either as a discrete mode switch with entry/exit criteria based on the magnitude of torque and MAP error, or as a continuous adjustment where the errors are directly used to determine the control extent.

[0022]   Figs. 2(a)-2(e) are a series of graphs that conceptually illustrate the proposed strategy in its continuous control implementation. During the first phase of the fast transient maneuver, one or more selected control parameter(s) (e.g., HF, FF and/or cam phasing) will be rapidly moved to an intermediate settings that facilitates the rapid delivery (and possibly over-delivery) of the requested torque. As soon as the requested torque is achieved and manifold pressure begins increasing as a result of turbo speed increasing, the control parameters are transitioned to their nominal fuel-optimal settings until the desired targets are achieved. During the initial phase, it may be desired to over-deliver air and manage the torque overshoot using spark retard. This further enhances the anti-lag potential of the control strategy. Even though this strategy purposely operates briefly at less fuel-efficient conditions, the result is faster and more accurate torque delivery which is expected to have a net positive effect on fuel economy.

[0023]   Referring next to Fig. 3, a representative method of managing a torque request increase during cylinder output level modulation operation of a turbocharged engine in accordance with one embodiment will be described. The process begins with the engine operating in a reduced displacement state as represented by block 202. This reduced displacement "initial" engine state can be skip fire, multi-level skip fire or multi-charge level operating mode with an effective firing density (eFD) of less than one (eFD < 1). In the initial

state, engine setting such as intake manifold pressure (MAP), valve timing, fuel charge, spark timing, etc. are set appropriately and the turbocharger compressor is operating at an initial pressure ratio.

[0024]   When a new torque request is received (as represented by block 204), the engine controller determines a target engine state as represented by block 206. The target engine state may involve a different effective firing density and/or a different target MAP (which may require a different target compressor pressure ratio) than the initial engine state.

[0025]   Some target intake manifold pressures can be readily achieved based on current operating conditions. However, others may require turbocharger compressor pressure ratios that are not immediately achievable given the current mass flow rate of air/gases through the engine. This distinction is represented by decision block 208 in Fig. 3.   If the target MAP is readily achievable without experiencing turbo lag, a transition is made to the target state as represented by block 210. However, if the target MAP is not readily achievable, (the "No" branch from decision block 208), efforts may be made to mitigate the lag (i.e., provide a fast torque response) in a fuel efficient manner as will be described in more detail below.

[0026]   One of the most common scenarios in which turbo lag occurs is accelerator tip-in. One such scenario is when the driver depresses the accelerator pedal when the engine is idling (or otherwise operating at a relatively low output level), thereby requesting significantly more engine torque. Of course, the same can occur anytime the driver (or an autonomous vehicle controller) significantly increases the engine torque request. In such cases the target engine state may have a desired intake manifold pressure (MAP) that cannot be immediately attained by the turbocharger, resulting in an actual engine output that is lower than the desired engine output due to turbo lag. Turbo lag can also occur in circumstances in which cylinder load demand increases (requiring a corresponding increase in the turbocharger compressor pressure ratio) as may occur when the firing fraction is reduced in skip fire operation of a boosted engine.

[0027]   At this point it is worth noting that a simple approach to managing the engine state transition is to simply transition to the target effective firing density and in parallel, command the turbocharger to deliver a target pressure ratio required to provide the target MAP. However, if the turbocharger is operating in a region where there is not a sufficient mass flow of air/gases through the turbocharger turbine, it will take time to spin the turbocharger up sufficiently to deliver the target compressor PR / MAP and there will be a corresponding torque sag due to this turbo lag.

[0028]   Returning to Fig. 3, in order to provide a faster torque response and thereby mitigate the turbo lag, actions are taken to increase the gas flow rate through the engine. This can be accomplished, at least in part, by transitorily increasing the effective firing density of the engine relative to both the initial and target eFDs (block 212, which follows the "No" branch from decision block 208). The higher eFD can be realized by increasing one or both of the high fire fraction (HF) and the firing fraction (FF). In some implementations, the transition to the intermediate eFD may be accomplished in a single step. In others, the increase may be aggressively ramped. Fig. 2(a) diagrammatically illustrates a linearly ramped approach. In still other approaches, the ramping may be controlled as a function of torque and MAP errors. When operating conditions permit, the air flow rate can be further increased by adjusting the cam settings to induct a larger air charge in each active cylinder working cycle as diagrammatically illustrated in Fig. 2(b).

[0029]   Notably, the intermediate eFD and cam setting are selected to increase airflow through the engine relative to both the airflow at the initial settings and the airflow at the target settings. Thus, in general the intermediate eFD is higher than the target eFD.

[0030]   Transitioning to the intermediate eFD serves multiple benefits. One benefit is that the higher eFD allows the boosted engine to more rapidly deliver the desired torque than it would if the target eFD is used. Thus, a faster torque response is provided improving drivability and performance. Additionally, use of a higher eFD increases the air/gas flow through the engine. The higher gas flow rate allows the turbocharger turbine to spin up more quickly – which, in turn facilitates reaching the target compressor ratio more quickly than it can be achieved by using the target eFD during the transition. Changes to cam settings to increase the air charge in the fired cylinders can further increase airflow.

[0031]   Once the engine is in a state where it can produce the desired torque, (as represented by block 214), the engine controller gradually reduces airflow through the engine in parallel with increasing the turbocharger's compressor pressure ratio to the target pressure ratio while continuing to deliver the requested torque (as represented by block 216). One aspect of this transition is gradually transitioning the effective firing density from the intermediate eDF to the target eFD. When appropriate, the cam settings can be gradually adjusted towards the target cam settings in parallel with the transition to the target eDF as represented by Fig. 2(b).

[0032]   The gradual reduction of airflow and/or effective firing fraction may be accomplished in a variety of manners. In some implementations, a linear ramp or other predefined path may be used. In others, the ramping may be controlled as a function of torque

and MAP errors. In some preferred embodiments, the effective firing density, the compressor pressure ratio, the cam setting and other engine settings are controlled such that the engine operates efficiently while neither producing excess torque nor experiencing a torque sag through the gradual transition from the intermediate eFD to the target eFD. Once the target eFD is attained, the engine operated in the target engine state as represented by block 218.

[0033] As will be appreciated by those familiar with skip fire engine control, fuel economy is generally improved with the use of lower firing fractions. Therefore, it is generally desirable to begin ramping down to the target eFD once the engine is producing the desired torque. However, the rate of the ramping down will be dictated in large part by engine airflow dynamics to avoid torque sags during the transition.

[0034] The manner that the effective firing density is changed during the transition may vary based on a variety of factors including the type of control supported by the engine controller, as well as the nature of the initial and target engine states. For example, if the engine controller supports skip fire engine operation, but not multi-level cylinder outputs, only the firing fraction can be adjusted. Conversely, if the engine controller supports multi-charge level operation, but not skip fire operation, then only the high fire fraction can be adjusted. When multi-level skip fire is supported, than one or both of high fire fraction and firing fraction can be adjusted.

[0035] In some specific embodiments, the transition from the initial settings to the intermediate settings is made without changing the requested compressor pressure ratio (i.e., while holding the compressor ratio constant). This allows the turbocharger to spin up quickly while rapidly transitioning to a state that is able to effectively deliver the desired torque. Once the engine is producing the desired torque at the intermediate state, the compressor pressure ratio can be gradually increased to the target pressure ratio while gradually reducing the operation effective firing density to the target eFD while continuing to deliver the desired torque. This two stage approach is illustrated in Figs. 2(a)-2(e). In the first stage the airflow through the engine is increased (by increasing eFD, adjusting the cam settings while holding the compressor pressure ratio constant. In throttled engines, the airflow can be further enhanced by opening the throttle. In the second stage, the compressor pressure ratio is increased while continuing to deliver the desired torque. Our testing has shown that this two stage approach can provide a fast torque response in a fuel efficient manner.

[0036] When the target conditions allow, it can be particularly desirable to control the eFD during the transition from the intermediate state to the target state by only modulating (gradually reducing) the high fire fraction (HF). This is most practical when the target engine state has a

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relatively lower high fire fraction. In some specific circumstances, the intermediate state may be a multi-level skip fire operating state that utilizes the target firing fraction and a high fire fraction that is higher than the target high fire fraction – e.g., a high fire fraction of "1" although lower high fire fractions may be used as appropriate. When the intermediate state has the same firing fraction (but higher high fire fraction) than the target state, the transition from the intermediate state to the target state can be accomplished by varying the high fire fraction (and potentially cam and other settings) while maintaining the firing fraction constant. Such an approach tends to have particularly good NVH characteristics.

[0037] It should be appreciated that in some applications, a torque reserve may be desired through the transition (that is, it may be desirable to maintain the ability to almost instantaneously increase to torque output through at least some of the transition). If such a torque reserve is desired, the gradual ramp down to the target eFD can be controlled so that the engine is capable of producing excess torque and the excess torque can be mitigated using conventional techniques such as spark retard.

[0038] It is worth noting that since the transition to the target eFD occurs more quickly when using an intermediate eFD that is higher than the target eFD, the overall fuel economy associated with the transition can often be improved relative to a direct transition from the initial engine state to the target engine state. This is because the target engine state is typically more fuel efficient than transitional states and thus the quicker transition to the more fuel efficient state reduces the overall fuel consumption associated with the transition.

[0039] The specific intermediate eFDs most suitable for use in specific transitions will vary based on a number of factors including the initial engine state, the target engine state, engine airflow dynamics, drivability concerns, NVH (noise, vibration and harshness) concerns, etc. As such, the specific intermediate eFDs used in specific circumstances may vary in accordance with the design goals of the manufacturer. In some circumstances, it may be desirable to use an effective firing density or a firing fraction of one (i.e. all cylinders firing) as the intermediate eFD. However, in many circumstances, better fuel efficiency and very good transitory response can be attained by using an intermediate eFD that is less than one. When the high fire fraction is a variable that can be controlled and the target eFD has a relatively low HF, in some specific operating circumstances it may be desirable to use a HF = 1 and the target firing as the intermediate eFD. When this is done, the transition from the intermediate eFD to the target eFD can be accomplished solely via ramping the high fire fraction which is particularly easy.

[0040]   Although only a few embodiments of the invention have been described in detail, it should be appreciated that the invention may be implemented in many other forms without departing from the spirit or scope of the invention. Therefore, the present embodiments should be considered illustrative and not restrictive and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

[0041]   The described approach has the benefit of providing a fast torque response to the driver's request for more power (or other cylinder output change requests) in a fuel efficient manner. The description above has focused primarily on varying the effective firing density (and especially the high fire fraction) to increase airflow through the turbocharger during transients that require a higher turbocharger compressor pressure ratio than can be a readily/rapidly achieved by directly commanding such a pressure ratio. However, it should be appreciated that in some specific instances a suitable airflow increase may be achieved through modulation of the cylinder air charge using cams alone.

[0042]   In some described embodiments, the spin-up of the turbocharger is accomplished while maintaining the compressor pressure ratio constant. This works well in both throttled and unthrottled engines. However, it should be appreciated that in some circumstances, the compressor pressure ratio may be increased somewhat between the initial and intermediate states if desired. In throttled engines, the MAP may actually be increased.

[0043]   The described approaches are very well suited for use in a wide variety of boosted internal combustion engines. The various described approaches work with engines that operate under a wide variety of different thermodynamic cycles, including diesel and other compression ignition engines, Otto cycle engines, Dual cycle engines, Miller cycle engines, Atkinson cycle engines, lean burn engines, Wankel engines and other types of rotary engines, mixed cycle engines (such as dual Otto and diesel engines), hybrid engines, radial engines, including virtually any type of four or two stroke piston engines, etc. It is also believed that the described approaches will work well with newly developed internal combustion engines regardless of whether they operate utilizing currently known, or later developed thermodynamic cycles. These include engines for virtually any type of vehicle – including cars, trucks, boats, aircraft, motorcycles, scooters, etc.; and virtually any other application that involves the firing of working chambers and utilizes a boosted internal combustion engine.

[0044]   Diesel and other compression ignition engines have unique requirements. In such engines the selection of the target and intermediate firing densities as well as the ramps between states may be dictated in large part by emissions related considerations such as maintaining a

desired temperature or temperature range in an exhaust emissions control system. Typically, the fuel charge, the air-fuel ratio and/or the exhaust gas recirculation (EGR) can be controlled in diesel and other compression ignition engines and those variables can incorporated into the turbocharger/torque control strategy.

[0045]   In throttled engines, the intake manifold pressure and thus the airflow through the engine may be further increased by opening the throttle if/when the initial engine state was at least partly throttled.

CLAIMS

What is claimed is:

1.   A method of managing a transition from a first engine state to a target engine state in a boosted engine configured to operate in a cylinder output level modulation mode, the boosted engine including a turbocharger having a turbine and a compressor, the first engine state having an associated first engine torque output, an associated first effective firing density and an associated first compressor pressure ratio, and the target engine state having an associated target engine torque output, an associated target effective firing density and an associated target compressor pressure ratio that is higher than the first compressor pressure ratio, the method comprising:

in response to a request to transition to the target operating state, directing the engine to transition to a second effective firing density that is higher than the first effective firing density and higher than the target effective firing density to increase a flow of gases through the engine and the turbocharger; and

after reaching the second effective firing density, gradually reducing an operational effective firing density from the second effective firing density to the target effective firing density while increasing an operational compressor pressure ratio to the target compressor ratio.

2.   A method as recited in claim 1 wherein the gradual reduction only begins after the engine is producing the target engine torque.

3.   A method as recited in claim 2 further comprising controlling the engine to deliver the target engine torque throughout the gradual reduction of the effective firing density from the second effective firing density to the target effective firing density.

4.   A method as recited in claim 1 wherein when the engine is not capable of immediately delivering the target engine torque at the target effective firing density and the gradual reduction of the effective firing density from the second effective firing density to the target effective firing density occurs does not begin until the engine is, or is expected to be, delivering the target engine torque and the target engine torque is delivered throughout the gradual reduction.

5.   A method as recited in claim 1 wherein the second effective firing density is less than one.

6.   A method as recited in claim 1 wherein the gradual reduction is accomplished at a constant firing fraction by varying a fraction of fired cylinder working cycles that are fired at a higher output level verses fired at a lower output level.

7.   A method as recited in claim 1 wherein the gradual reduction is substantially linear.

8.   A method as recited in claim 1 wherein the gradual reduction is controlled as a function of observed torque and intake manifold pressures relative to the target engine torque and a target intake manifold pressure respectively.

9.   A method as recited in claim 1 wherein the gradual reduction is accomplished by gradually reducing an operational firing fraction.

10.   A method as recited in claim 1 wherein the gradual reduction is accomplished by reducing both an operational firing fraction and an operational high fire fraction that is indicative of a percentage of fired cylinder working cycles that are fired at a higher output level verses fired cylinder working cycles that are fired at a lower output level.

11.   A method as recited in claim 1 wherein the transition to a second effective firing density is immediate.

12.   A method as recited in claim 1 wherein the transition to a second effective firing density is gradual.

13.   A method as recited in claim 1 wherein an overall fuel efficiency associated with the transition from delivering the current engine torque to delivering the target engine torque using the intermediate second effective firing density is higher than a transition overall fuel efficiency would be if an immediate change to the target effective firing density at the target compressor pressure ratio were commanded.

14.   A method as recited in claim 1 wherein the request to transition to the target state is due to accelerator tip-in.

15.   A method as recited in claim 1 wherein the target effective firing density is less than or equal to the first effective firing density and the target compressor pressure ratio is higher than the first compressor pressure ratio.

16.   An engine controller for controlling a boosted engine including a turbocharger having a turbine and a compressor and configured to direct operation of the engine in a cylinder output level modulation mode and to manage a transition from, the engine controller being further configured to:

in response to a selected torque request, determine that a transition from a first engine state to a target engine state is desired, the first engine state having an associated first engine torque output, an associated first effective firing density and an associated first compressor pressure ratio, and the target engine state having an associated target engine torque output, an

associated target effective firing density and an associated target compressor pressure ratio that is higher than the first compressor pressure ratio;

in response to the determination that the transition from the first engine state to a target engine state is desired, direct the engine to transition to a second effective firing density that is higher than the first effective firing density and higher than the target effective firing density thereby increasing a flow of gases through the engine and the turbocharger; and

after reaching the second effective firing density and producing the target torque at the second effective firing density, gradually reducing an operational effective firing density from the second effective firing density to the target effective firing density while increasing an operational compressor pressure ratio to the target compressor ratio.

17.   An engine controller for controlling a boosted engine including a turbocharger having a turbine and a compressor and configured to direct operation of the engine in a cylinder output level modulation mode and to manage a transition from, the engine controller being further configured to:

in response to a selected torque request, determine that a transition from a first engine state to a target engine state is desired, the first engine state having an associated first engine torque output, an associated first effective firing density an associated first compressor pressure ratio and a first mass airflow rate, and the target engine state having an associated target engine torque output, an associated target effective firing density, a target mass airflow rate and an associated target compressor pressure ratio that is higher than the first compressor pressure ratio;

in response to the determination that the transition from the first engine state to a target engine state is desired, direct the engine to transition to a second engine state while maintaining the first compressor pressure ratio, the second engine state having second mass airflow rate that is higher than the first mass airflow and higher than the target effective mass airflow rate; and

after reaching the second engine state and producing the target torque at the second engine, gradually reducing an operational mass airflow rate to the target effective firing density while increasing an operational compressor pressure ratio to the target compressor ratio.

after reaching the second engine state and producing the target torque at the second engine state, gradually reducing an operational mass airflow rate to the target effective mass airflow rate while increasing an operational compressor pressure ratio to the target compressor ratio.

18.   An engine controller as recited in claim 17 wherein the second effective firing density is higher than the first and target effective firing densities and variations in an operational mass airflow rate that occur through the transition are accomplished at least in part through variations in an operational mass airflow rate.

19.   An engine controller as recited in claim 17 wherein variations in an operational mass airflow rate that occur through the transition are accomplished at least in part by varying operational cam settings throughout the transition.

20.   An engine controller as recited in claim 17 wherein the engine is a throttled engine and the increase in the operational mass airflow rate in the transition from the first engine state to the second engine state is accomplished at least in part by varying an operational throttle setting.

21.   An engine controller as recited in claim 17 wherein the engine is one selected from the group consisting of a spark ignition engine, a diesel engine and a compression ignition engine.

22.   A method of managing a transition from a first engine state to a target engine state in a boosted engine configured to operate in a cylinder output level modulation mode, the boosted engine including a turbocharger having a turbine and a compressor, the first engine state having an associated first torque output, an associated first effective firing density and an associated first compressor pressure ratio, and the target engine state having an associated target torque output, an associated target effective firing density and an associated target compressor pressure ratio that is higher than the first compressor pressure ratio, the method comprising:

in response to a request to transition to the target operating state, causing the engine to transition to a second effective firing density that is higher than the first effective firing density and higher than the target effective firing density while substantially maintaining the first compressor pressure ratio;

after the target torque has been achieved operating at the second effective firing density and the first compressor pressure ratio, gradually reducing an operational effective firing density from the second effective firing density to the target effective firing density while gradually increasing an operational compressor pressure ratio from the first compressor pressure ratio to the target compressor pressure ratio and continuing to output substantially the target torque.

23.   A method as recited in claim 22 performed while the engine is operating in a multi-level skip fire operational mode.

24.   A method as recited in claim 22 performed while the engine is operating in a multi-charge level operational mode.

25.   A method as recited in claim 22 performed while the engine is operating in a skip fire operational mode.

26.   A method as recited in any of claims 1-4 or 22-25 wherein the second effective firing density is less than one.

27.   A method as recited in any of claims 1-4, 22-24 or 26 wherein the gradual reduction is accomplished at a constant firing fraction by varying a fraction of fired cylinder working cycles that are fired at a higher output level verses fired at a lower output level.

28.   A method as recited in any of claims 1-4 or 22-27 wherein the gradual reduction is substantially linear.

29.   A method as recited in any of claims 1-4 or 22-27 wherein the gradual reduction is controlled as a function of observed torque and intake manifold pressures relative to the target engine torque and a target intake manifold pressure respectively.

30.   A method as recited in any of claims 1-4, 22-23, 26 or 28-29 wherein the gradual reduction is accomplished by gradually reducing an operational firing fraction.

31.   A method as recited in any of claims 1-4, 22-23, 26 or 28-29 wherein the gradual reduction is accomplished by reducing both an operational firing fraction and an operational high fire fraction that is indicative of a percentage of fired cylinder working cycles that are fired at a higher output level verses fired cylinder working cycles that are fired at a lower output level.

32.   A method as recited in any of claims 1-4 or 22-31 wherein the transition to a second effective firing density is immediate.

33.   A method as recited in any of claims 1-4 or 22-31 wherein the transition to a second effective firing density is gradual.

34.   A method as recited in any of claims 1-4 or 22-33 wherein an overall fuel efficiency associated with the transition from delivering the current engine torque to delivering the target engine torque using the intermediate second effective firing density is higher than a transition overall fuel efficiency would be if an immediate change to the target effective firing density at the target compressor pressure ratio were commanded.

35.   A method as recited in any of claims 1-4 or 22-34 wherein the request to transition to the target state is due to accelerator tip-in.

36.   A method as recited in any of claims 1-4 or 22-35 wherein the target effective firing density is less than or equal to the first effective firing density and the target compressor pressure ratio is higher than the first compressor pressure ratio.

37.   An engine controller configured to perform the method of any of claims 1-15 or 22-36.

38.   An engine controller as recited in any of claims 16, 17 or 37 wherein the second effective firing density is higher than the first and target effective firing densities and variations in an operational mass airflow rate that occur through the transition are accomplished at least in part through variations in an operational mass airflow rate.

39.   An engine controller as recited in any of claims 16, 17 or 37-38 wherein variations in an operational mass airflow rate that occur through the transition are accomplished at least in part by varying operational cam settings throughout the transition.

40.   An engine controller as recited in any of claims 16, 17 or 37-39 wherein the engine is a throttled engine and the increase in the operational mass airflow rate in the transition from the first engine state to the second engine state is accomplished at least in part by varying an operational throttle setting.

41.   An engine controller as recited in any of claims 16, 17 or 37-40 wherein the engine is one selected from the group consisting of a spark ignition engine, a diesel engine and a compression ignition engine.
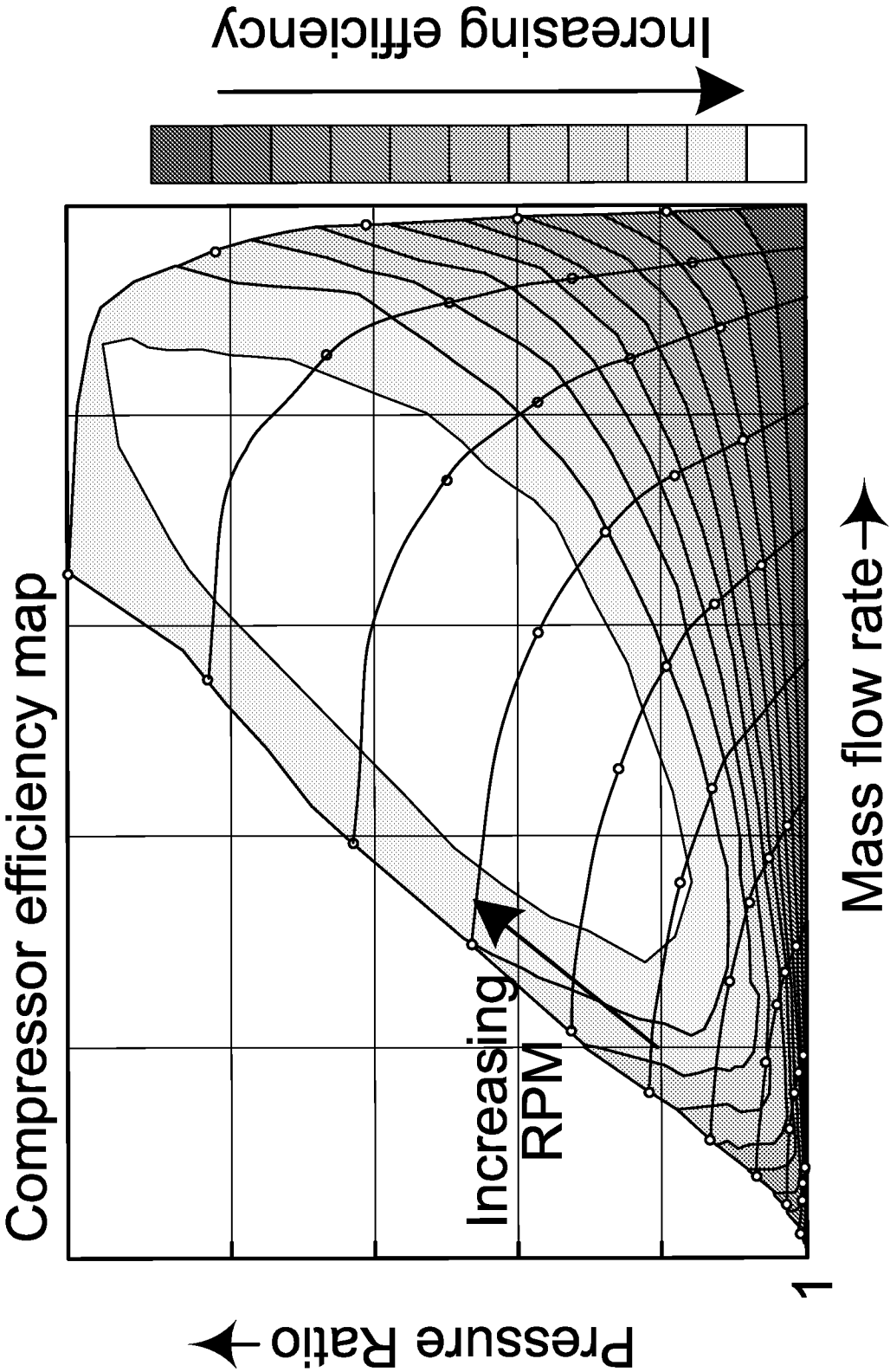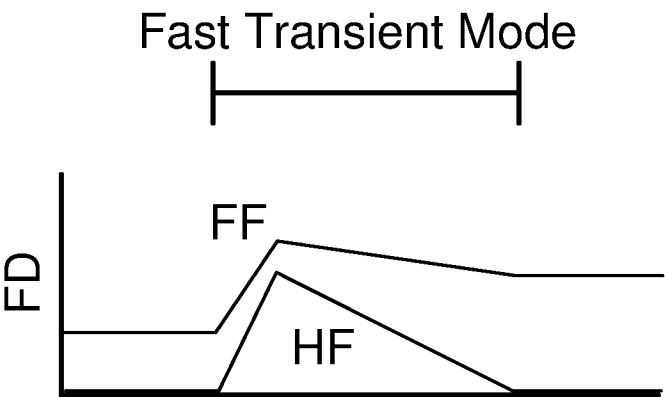
FIG. 1

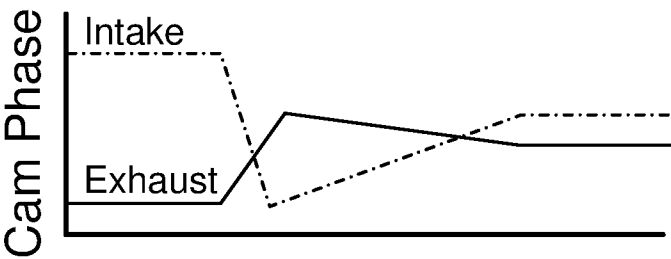Fast Transient Mode
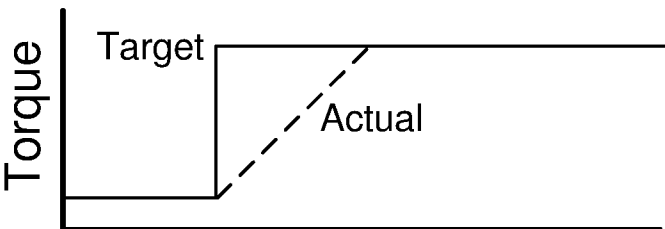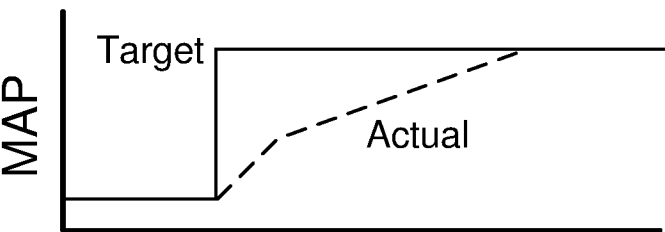
FIG. 2A

FIG. 2B

FIG. 2C

FIG. 2D
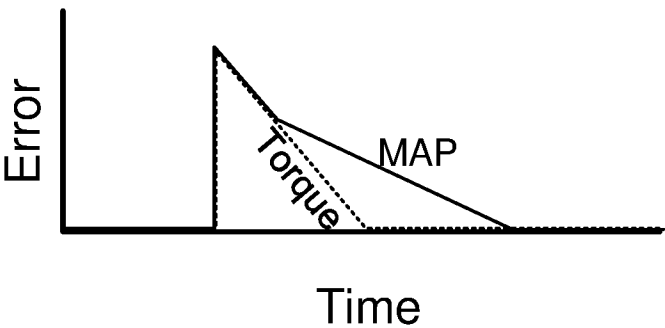
FIG. 2E
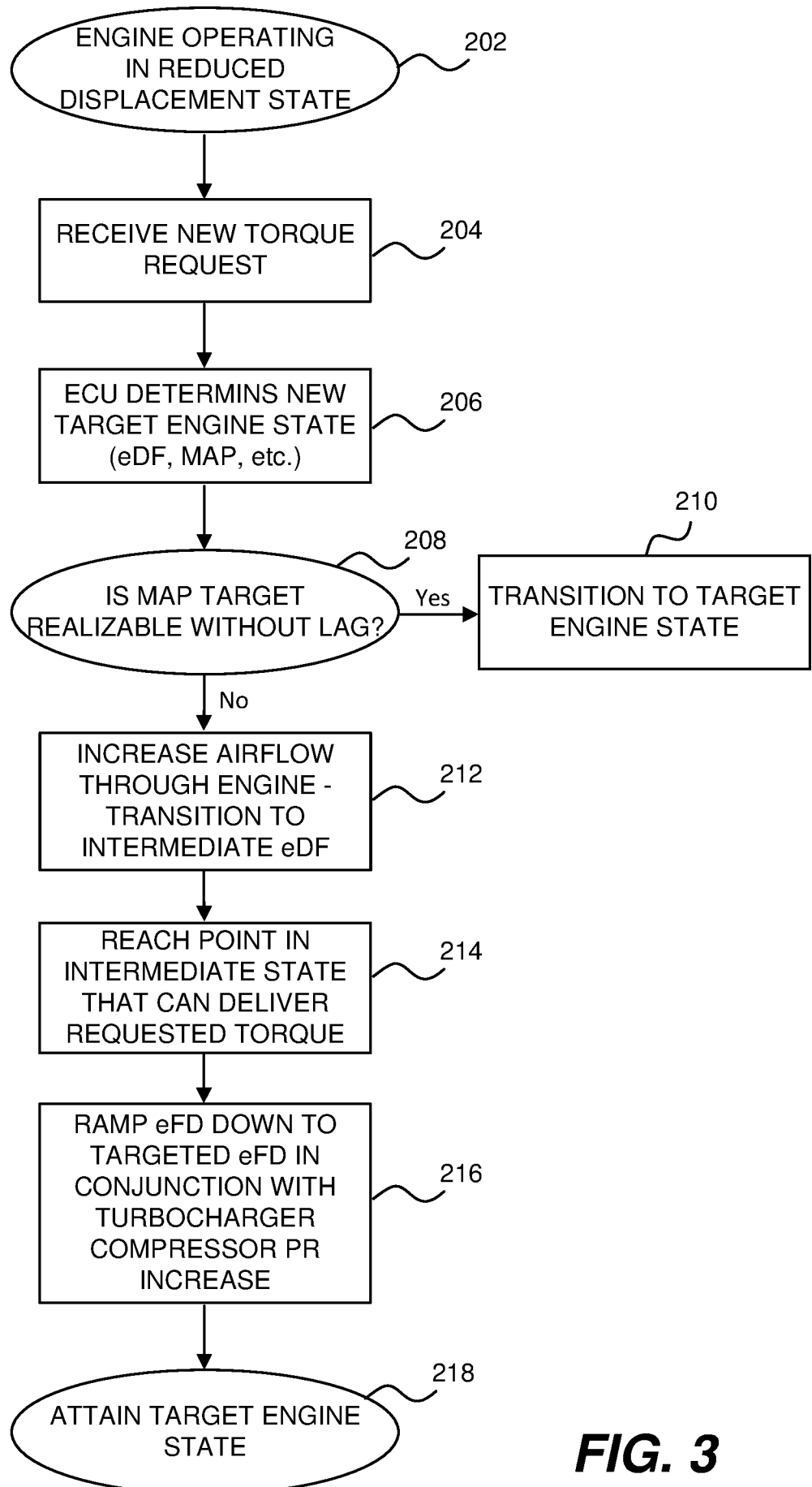
Time

```
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        │   ENGINE OPERATING      │      202
        │   IN REDUCED            │
        │   DISPLACEMENT STATE    │
        └───────────┬─────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │   RECEIVE NEW TORQUE    │      204
        │   REQUEST               │
        └───────────┬─────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │   ECU DETERMINS NEW     │      206
        │   TARGET ENGINE STATE   │
        │   (eDF, MAP, etc.)      │
        └───────────┬─────────────┘
                    │
                    ▼                                          210
        ┌─────────────────────────┐      Yes    ┌──────────────────────┐
        │   IS MAP TARGET         │ ──────────▶ │ TRANSITION TO TARGET │
        │ REALIZABLE WITHOUT LAG? │    208      │   ENGINE STATE       │
        └───────────┬─────────────┘             └──────────────────────┘
                    │ No
                    ▼
        ┌─────────────────────────┐
        │   INCREASE AIRFLOW      │      212
        │   THROUGH ENGINE -      │
        │   TRANSITION TO         │
        │   INTERMEDIATE eDF      │
        └───────────┬─────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │   REACH POINT IN        │      214
        │   INTERMEDIATE STATE    │
        │   THAT CAN DELIVER      │
        │   REQUESTED TORQUE      │
        └───────────┬─────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │   RAMP eFD DOWN TO      │
        │   TARGETED eFD IN       │
        │   CONJUNCTION WITH      │      216
        │   TURBOCHARGER          │
        │   COMPRESSOR PR         │
        │   INCREASE              │
        └───────────┬─────────────┘
                    │
                    ▼
        ┌─────────────────────────┐      218
        │   ATTAIN TARGET ENGINE  │
        │   STATE                 │
        └─────────────────────────┘
```

FIG. 3

A.   CLASSIFICATION OF SUBJECT MATTER

F02D 41/00(2006.01)i; **F02D 37/02**(2006.01)i; **F02D 13/06**(2006.01)i; **F02D 17/02**(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B.   FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F02D 41/00(2006.01); F01N 3/20(2006.01); F02B 37/00(2006.01); F02B 37/12(2006.01); F02B 37/18(2006.01); F02D 23/00(2006.01); F02D 29/00(2006.01); F04D 25/04(2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: transition, target engine state, effective firing density, boosted engine, compressor pressure ratio

C.   DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2019-0226378 A1 (TULA TECHNOLOGY, INC.) 25 July 2019 (2019-07-25) paragraphs [0028]-[0111]; claims 14-15; and figures 1A, 3, 6A	1-41
Y	US 2017-0350313 A1 (LAWRENCE et al.) 07 December 2017 (2017-12-07) paragraph [0029]; claims 1, 3; and figure 1	1-41
Y	US 2005-0274357 A1 (MATTHEWS et al.) 15 December 2005 (2005-12-15) paragraph [0016]; and figure 1	20,40
A	JP 09-177555 A (TOYOTA MOTOR CORP.) 08 July 1997 (1997-07-08) paragraphs [0019]-[0056]; and figures 1-8	1-41
A	US 9574489 B2 (BOISE STATE UNIVERSITY) 21 February 2017 (2017-02-21) claims 1-20; and figures 1-4	1-41

☐ Further documents are listed in the continuation of Box C.   ☑ See patent family annex.

* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "D" document cited by the applicant in the international application "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
06 December 2021	**07 December 2021**

Name and mailing address of the ISA/KR	Authorized officer
Korean Intellectual Property Office **189 Cheongsa-ro, Seo-gu, Daejeon** **35208, Republic of Korea**	**BAHNG, SEUNG HOON**
Facsimile No. **+82-42-481-8578**	Telephone No. **+82-42-481-5560**

Form PCT/ISA/210 (second sheet) (July 2019)

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